Proposal of a resonant controller for a three phase four wire grid-connected shunt hybrid filter

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***Abstract* -- This paper present a three-phase four wire hybrid filter able to perform a selective cancellation of harmonic currents based on resonant controllers. As it will be shown in this work, this kind of control permits to enhance the bandwidth of the filter controller, without hindering the stability of the system. In addition a new hybrid filter topology, that permits to cancel out the homopolar harmonics, is presented in this paper. The good performance of this new topology as well as the proposed controller will be evaluated by means of simulations and experimental results.**

***Index Terms*— Harmonics, power filters, hybrid power filters, passive power filters, active power filters, reactive power compensation.**

I. INTRODUCTION

The injection of harmonic currents into the grid, due to the widespread usage of grid-connected non linear loads, is still an important problem in the electrical networks, especially in low voltage systems [1]. In this kind of lines the effect of the harmonics can be particularly harmful at the neutral conductor, due to the circulation of zero sequence harmonic currents.

In reference [2] an exhaustive review of shunt and series filter topologies was carried out. In this paper it is shown how the filtering applications based on passive filters are low cost, although its filtering capability is limited. On the other hand, active filters are presented as an ideal filtering system, but a high power converter is required in many applications, what increases significantly the cost. Finally, the performances of several hybrid topologies, that mix active and passive components, are discussed as well.

In [3] and [4] the typical control structures for three phase shunt hybrid filters were introduced. It should be pointed out that the presented filters, as well as many other applications based on hybrid topologies, are devoted to cancel out just the positive and negative sequence current harmonics.

On the other hand, there are filters able to minimize the zero sequence currents by means of using delta-wye transformers or zig-zag inductances [5]. However these systems do not permit dealing the entire problem of the harmonics either, since no action regarding the positive-negative sequence ones can be performed.

This paper aims to tackle a general solution for the simultaneous cancellation of the positive-negative and zero sequence harmonics. For doing that so, this paper presents a shunt hybrid filter topology that makes possible to treat jointly both problems. The main issue of this work is devoted to design a control system, based on resonant controllers [6], that permits to carry out a selective harmonic cancellation and the compensation of transport delays in the control loop. These features enhance the general operation of hybrid filters, while they guarantee a wider stability margin for higher gains in the control system, something that increases finally the filtering bandwidth. This is a critical point in applications based on hybrid filters. As it will be shown in the following, these controllers contribute also to cancel out the effects of resonances as well as to improve the current control.

II. DESCRIPTION OF THE FILTER TOPOLOGY

The proposed hybrid filter topology consists of a passive LC filter tuned to the sixth harmonic, in series with a three legs inverter, whose DC bus is connected to the neutral-wire [7]. This connection is carried out through an inductance that resonates with the previous filter to the third harmonic. The diagram in Fig. 1 shows the connection, to a three phase four wire grid, of the presented filter.

The model of the grid includes the impedance of the feeding transformer, that supplies power to a group of non linear loads, that produce positive-negative and zero sequence harmonics.

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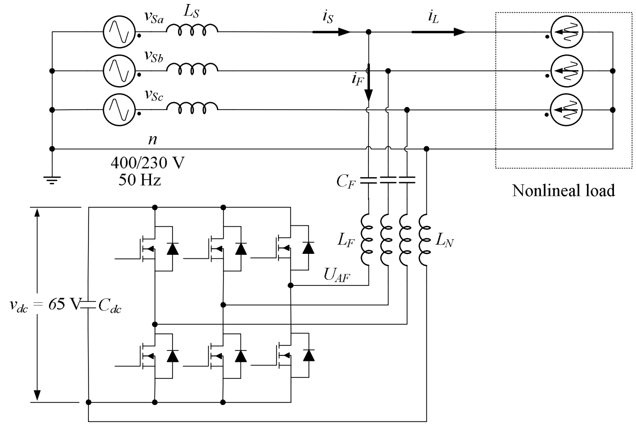

Fig. 1. Shunt hybrid filter connection to a three phase four wire power system

The passive filter of Fig.1 presents a resonance frequency for positive-negative sequence (pn-seq) components and another one for the zero sequence (z-seq) components [8]. These resonance frequencies are:

$$f_{12} = \frac{1}{2\pi}\frac{1}{\sqrt{L_F\,C_F}}, \tag{1}$$

$$f_0 = \frac{1}{2\pi}\frac{1}{\sqrt{\left(L_F + 3L_N\right)C_F}}, \tag{2}$$

being f_{12} the resonance frequency for pn-seq components, and f_0 the resonance frequency for z-seq components, respectively.

The passive filter topology presented in this paper is suitable for working as a shunt passive or hybrid power filter simultaneously draining pn-seq current harmonics at f_{12} and z-seq current harmonics at frequency f_0. It is worth to remark that currents drained by the pn-seq circuit and the z-seq circuit are completely independents. This is a crucial characteristic when the z-seq resonance frequency is set near to the fundamental grid frequency, e.g., f_0=150 Hz for a 50 Hz grid. Under such operating conditions, the z-seq circuit does not absorb any current at the fundamental grid component, that normally contains only a positive-sequence component.

III. Control of the Filter

The current at the grid side can be expressed according to (3), where it is considered that the output voltage of the inverter is proportional to the current (4).

$$I_{Sh} = I_{Lh}\left(\frac{Z_F}{Z_F + Z_S + k}\right) + \frac{U_{Sh}}{Z_F + Z_S + k}, \tag{3}$$

$$U_{AFh} = I_{Sh}\cdot k, \tag{4}$$

being I_{Sh} the h harmonic current component at the grid side, I_{Lh} the load current, Z_F the impedance of the passive filter, Z_S the source impedance, k the gain of the closed control loop, U_{Sh} the voltage at each harmonic that appear in the grid, and finally $U_{AFh,}$ that corresponds to the power converter's output voltage for each harmonic.

In Fig. 2 the layout of the conventional control diagram for a hybrid filter is shown. Considering this structure, and according to (3) and (4), it can be concluded that the average value of I_S trends to zero if the k constant increases.

This kind of control is carried out through a digital controller that, in its turns, operates a PWM modulated inverter.

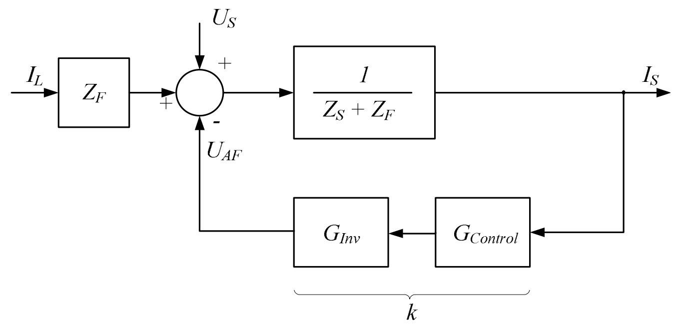

Fig. 2. Conventional control diagram of a hybrid filter

Therefore, a transport delay, τ_d , should be considered in the control loop, as this effect is able to unstabilize the system if the gain is high enough. This issue is shown in the bode diagram of Fig. 3, where the Gain and Phase of the system is depicted with and without the effect of the delay. In the phase graph of the bode it can be notice how, as a consequence of the delay, the phase and gain margins can change significantly.

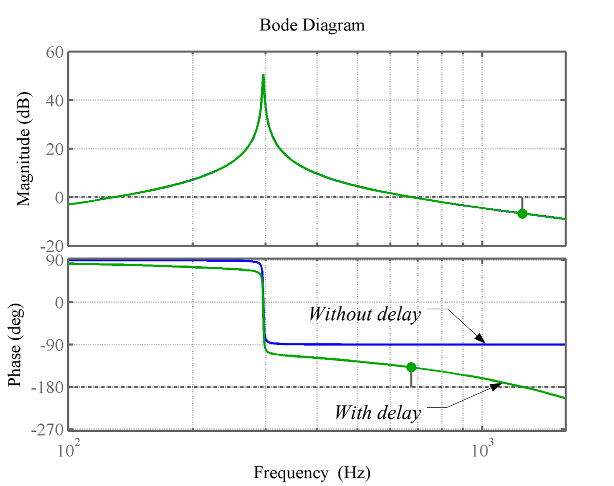

Fig. 3. Open loop bode diagram of the conventional control system

These plots stand out that an increase in the open loop gain harms the stability of the system, until arriving to a maximum value where it becomes unstable. This limit is given for the k_{MAX} gain. This value can be predicted thanks to (5).

$$k_{MÁX} = \frac{\pi\left(L_S + L_F\right)}{2\tau_d}, \tag{5}$$

On the other hand, the gain limitation does not permit to achieve optimal filtering results, as a matter of the stability of the system. Due to this tradeoff between stability and performance it is of great interest to find solutions oriented to compensate the control delays, which are introduced by the digital control systems or the by the intrinsic dynamics of the power converter.

IV. Selective Harmonic Filtering

A selective harmonic filtering enables cancelling, in a preferable way, specific harmonic frequencies. This kind of selective cancellation can be carried out using resonant controllers, tuned at the selected frequency [9]. These controllers are constituted basically by a lowpass filter and a proportional gain, whose function is described in (6).

$$G_{DC} = K_P + \frac{K_I \cdot \omega_c}{s + \omega_c}, \tag{6}$$

Such controllers permits to control positive and negative sequence components, while those based on a PI in a synchronous reference frame needs to build decoupled loops for controlling both symmetrical components.

In Fig. 4 the equivalence between a generic controller, in a synchronous reference frame, G_{DC}, with an additional delay, φ, and their associated resonant controller, $G_{AC\varphi}$, able to give rise to the same output signals, is shown.

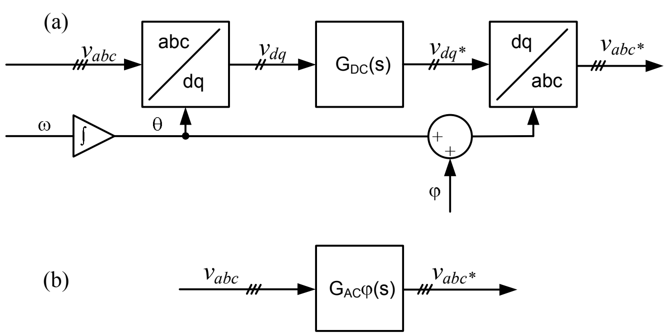

Fig. 4. Equivalent control structures based on a syncrhonous reference frame with additional delay (a), and a resonant controller (b).

The equivalent equations can be found, for any frequency ω, thanks to (7), where φ is the additional phase that should be incorporated to the output function in order to compensate the controller's delay.

$$G_{AC\varphi}(s) = \frac{\cos(\varphi)\cdot[G_{DC}(s-j\omega)+G_{DC}(s+j\omega)]}{2} \\ \frac{j\,\mathrm{sen}(\varphi)\cdot[G_{DC}(s-j\omega)-G_{DC}(s+j\omega)]}{2} \tag{7}$$

Obtaining finally the equivalent resonant controller's function, as shown in (8).

$$G_{AC\varphi} = K_p + \frac{2K_I\omega_c(as+b)}{s^2+2\omega_c s+\omega^2}, \qquad a = \cos\varphi \;\; ; \;\; b = \omega_c\cos\varphi - \omega\sin\varphi. \tag{8}$$

This function is applied to each harmonic that must be controlled, as it is shown in Figure 5. In this figure the blocks: k_5, k_7, k_{11}, and k_{13} are resonant controllers, obtained by means of the equation (8), whose resonance frequency match fhe value of the 5th, 7th, 11th and 13th harmonic respectively. The delay angle, φ_h , to be compensated by each controller is found by means of (9).

$$\varphi_h = \omega_h \tau_d. \tag{9}$$

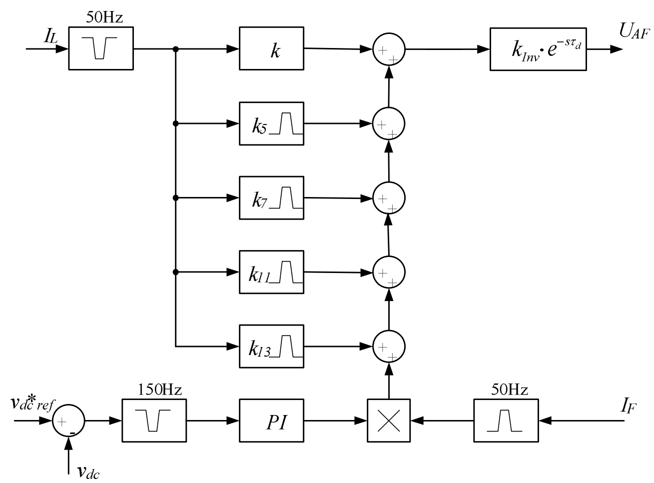

Fig. 5. Resonant controller block diagram

The resulting open loop frequency response is displayed in Figure 6, where the gain peaks that corresponds to the selected harmonics, can be easily noticed. The K_p and K_i values of each resonant controllers can be limited thanks to an anti-windup control, which permits controlling the inverter's voltage and the output current of the filter according to their operation limits.

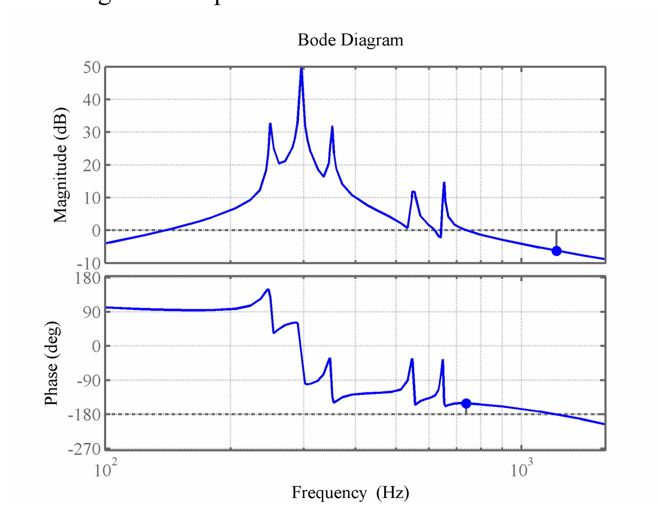

Fig. 6. Open loop bode diagram of the resonant control system

V. Simulation and Experimental Results

The results of the simulation, available in Fig. 7, show the behaviour of the load, filter and grid currents respectively.

There it can be highlighted the satisfactory response of the hybrid filter, that is able to cancel almost all the positive-negative sequence harmonics provided by the load.

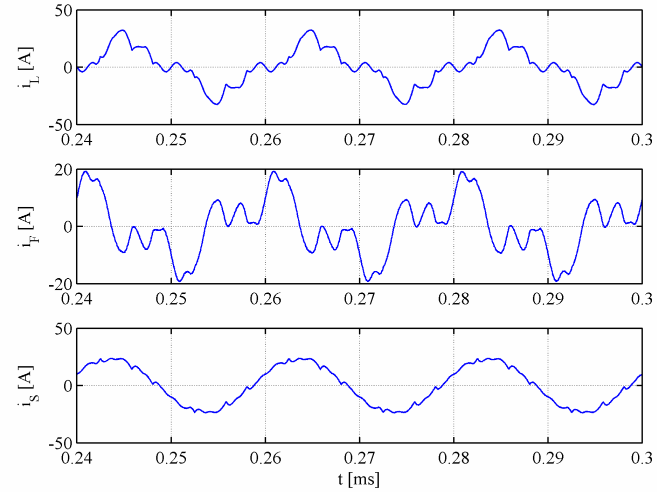

Fig. 7. Currents at the phase wires

In its turns the homopolar currents are also filtered at the neutral-wire of the grid, as it is shown in Fig. 8, where no third harmonic can be found although is being generated by the load.

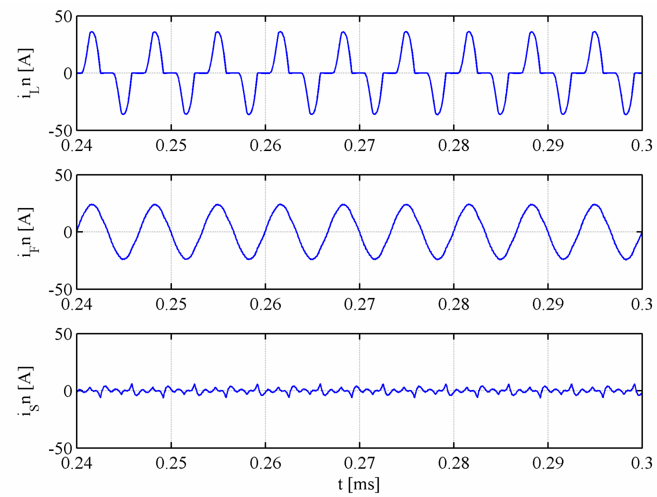

Fig. 8. Currents at the neutral wire

The Fig. 9 shows the workbench layout where the proposed control will be the experimentally tested. There the non lineal load is modelled by means of a group of one-phase rectifiers connected to the grid, in parallel with the hybrid filter. The LC filter has been tuned to 300 Hz, while the resonance of the neutral wire filter has been adjusted to 150 Hz. The control is performed by a digital signal processing dsPIC30F6010, responsible in addition of the PWM modulation (14.4 kHz) that operates the low voltage MOSFET inverter.

In Fig. 10 the experimental results obtained with the presented prototype when the filtering algorithm is enabled are shown.

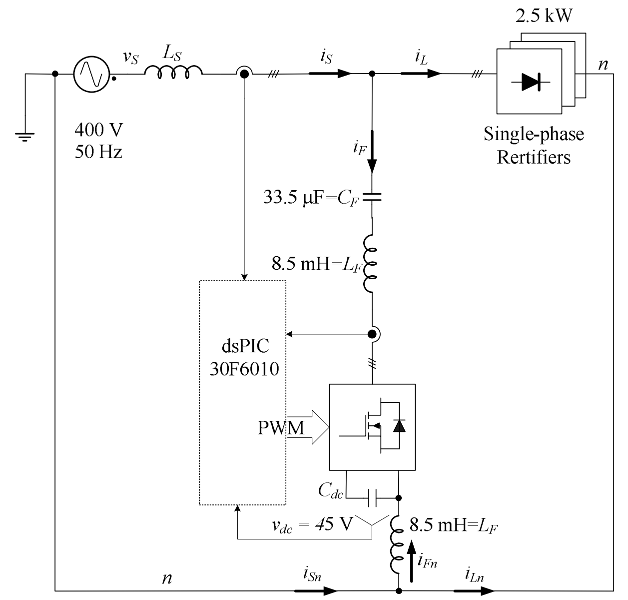

Fig. 9. Currents at the neutral wire

In the figure the currents, which flow through the phase and neutral wire, at the load and grid side are depicted. As it can be clearly noticed from the figure, before the enable of the filter the inverter was giving no current, and the filter setup was only acting as a passive filter. Under these conditions the filtering capability of the system is very low and a resonance appears between the capacitor of the filter and the grid impedance.

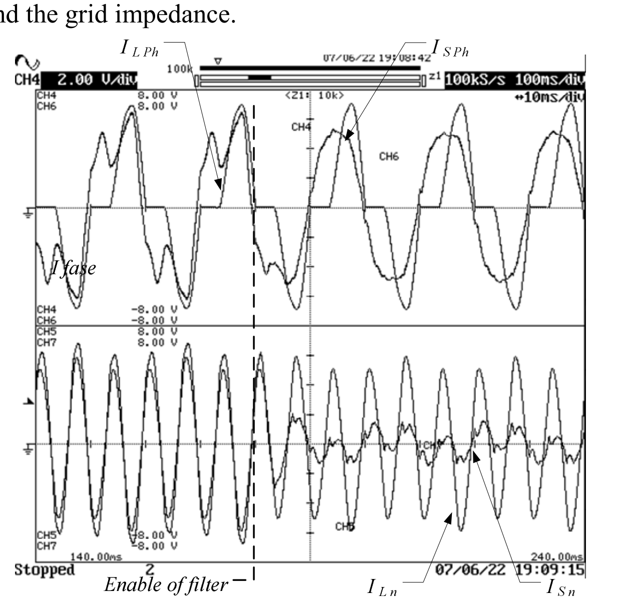

Fig. 10. Currents at the phase and neutral wire during the connection transient of the filter.

Once the control is enabled, the filter is able to cancel out the harmonics after 20ms, as shown in the plot. The grid side currents become almost completely sinusoidal and the 150Hz current at the neutral wire is being strongly reduced.

The performance of the hybrid filter was tested as well considering the sudden connection of an harmonic load to the network, able to inject zero sequence current. The results obtained in this experiment are shown in Fig. 11. The currents displayed in the figure are: the load current at one phase wire, the current at the neutral wire of the load, the grid side current at one phase wire and the neutral current at the grid side. As it can be seen in the figure, the hybrid filter is able to eliminate the harmonic distortion in the phase currents while reducing at the same time harmonics at the neutral wire.

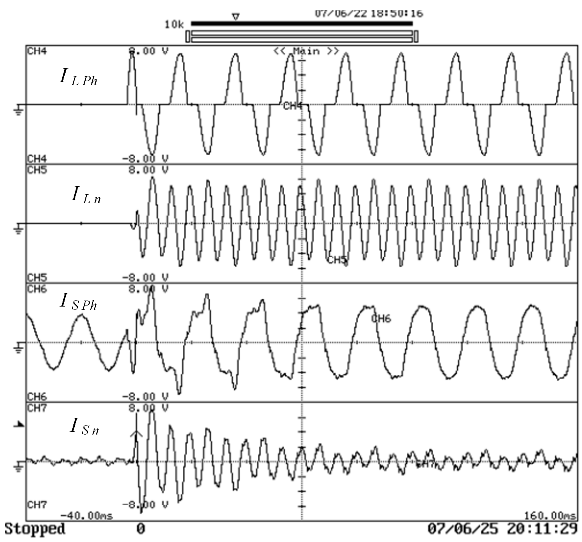

Fig. 11. Response of the hyrbid filter when a harmonic load is suddenly connected.

VI. CONCLUSIONS

The use of resonant controllers permits an effective selective harmonics cancellation, as it was demonstrated in the previous section where the 3rd, 5th, 7th, 11th and 13th components are almost completely eliminated. It is also necessary to stand out the good results obtained thanks to the double tuning of the passive filter one for a positive-negative sequence harmonic and another for a zero sequence one. Regarding the proposed topology, it can be concluded that the connection of the hybrid filter's DC bus to the neutral wire enables the control of a three phase four wire grid without including an extra leg to the conventional inverter. This contributes to the simplicity of the control, and also to the reduction of the filter's cost.

Finally it can be assured that the present paper proposes a control system, based on resonant controllers, that offers a general solution for the positive-negative and zero sequence harmonic cancellation by means of using a hybrid filter. Besides, the proposed control is also able to compensate the digital controller's delay, improving thus the stability of the system for high gains in the loop.

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